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NONLINEAR AEROELASTICITY FOR HYPERSONIC FLIGHT VEHICLES

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Final Report

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o Built a multidisciplinary system for nonlinear, trimmed, static aeroelastic analysis of air vehicles.

o Integrated all modules

- CFL3D	Performs aero (Euler/Navier-Stokes) analysis
- COMETRAN	Maps aero forces to structural nodes
- PATRAN	Maps temperatures to structural nodes
- NASTRAN	Performs structural analysis
- Spline3D	Maps structural deformation to aero grid
- CSCMDQ or RexMesh	Perturbs aero volume grid
- TRIM	Finds control surface deflections to zero-out pitching moment
- DEFLECT	Deflects control surfaces and perturbs aero grid

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High Speed Aerodynamics Group — Loads and Dynamics Group

Nonlinear Aeroelasticity for Hypersonic Flight Vehicles

Contract No. F49620-00-C-0018
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Final Report
15 April 2000 – 30 November 2002

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The Boeing Company - Phantom Works
Huntington Beach, CA

Dedicated to the Memory of

Scott D. Zillmer

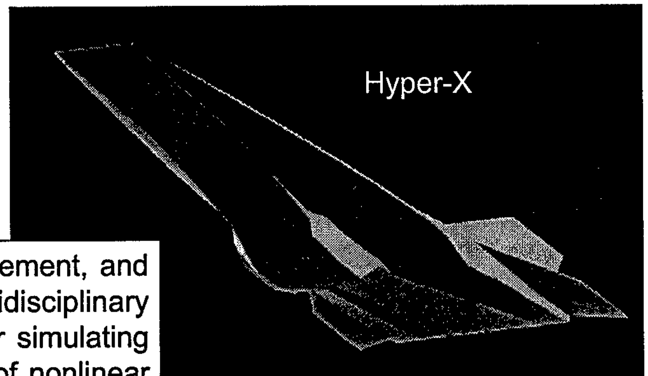
Boeing Associate Technical Fellow

2 December 1956 – 12 April 2002

Contents

Objective

High Speed Aerodynamics Group — Loads and Dynamics Group



Formulate, implement, and validate a multidisciplinary analysis tool for simulating the interaction of nonlinear aerodynamics, nonlinear structures, and flight controls for hypersonic flight vehicles

PHANTOM WORKS — BOEING

Hypersonic vehicles, like the Hyper-X, have unique aerodynamics/structures/ controls/propulsion interactions. Their aerodynamics is dominated by the fuselage and their wings are all-moving control surfaces. These missile-like configurations also feature highly integrated airbreathing propulsion systems with thin cowls. The shell structures of these cowls have tight geometric requirements for the inlet and the finely tuned shock systems to work. On the other hand, these cowls are subject to aerothermoelastic distortions which can significantly degrade the efficiency of the propulsion system. Hypersonic vehicles are also characterized by (relatively) cold and hot structures. To prevent overheating and to control thermal stress, accurate estimates of the temperature distribution throughout the vehicle are required.

Currently, the analysis of hypersonic vehicles rely primarily on methods that use linear structures and linear aerodynamics. Today, advances in computational fluid dynamics (CFD) and computer technology permit a limited number of nonlinear aerodynamic analyses. Thus far, this approach has not succeeded in reaching the goal of producing a viable hypersonic vehicle.

As a first step towards this goal, the objective of this project is to develop a multidisciplinary analysis tool for modeling the interaction of nonlinear aerodynamic, nonlinear structures, and flight controls for hypersonic vehicles.

Summary of Progress

High Speed Aerodynamics Group — Loads and Dynamics Group

- Built a multidisciplinary system for nonlinear, trimmed, static aeroelastic analysis of air vehicles.
- Integrated all modules
  - CFL3D : Performs aero (Euler/Navier-Stokes) analysis
  - COMETRAN : Maps aero forces to structural nodes
  - PATRAN : Maps temperatures to structural nodes
  - NASTRAN : Performs structural analysis
  - Spline3D : Maps structural deformation to aero grid
  - CSCMDO or FlexMesh : Perturbs aero volume grid
  - TRIM : Finds control surface deflections to zero-out pitching moment
  - DEFLECT : Deflects control surfaces and perturbs aero grid
- Limited testing completed

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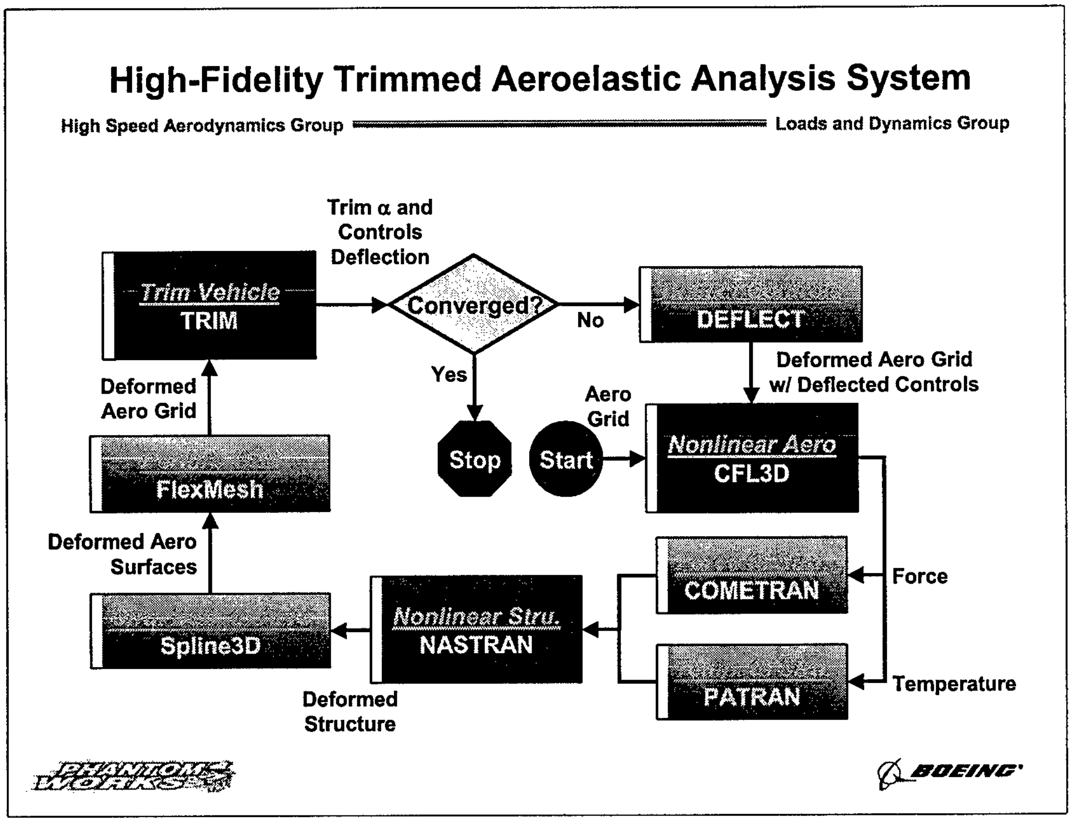
A prototype multidisciplinary design analysis system for trimmed aeroelastic analysis of air vehicles, using nonlinear aerodynamics and nonlinear structural analyses, has been completed. In order to facilitate distributed computing, the various modules -- most of them off-the-shelf -- were integrated using Phoenix Integrations ModelCenter. The primary modules are CFL3D and NASTRAN. CFL3D performs nonlinear aerodynamic (Euler/Navier-Stokes) analysis, while NASTRAN performs the nonlinear structural analysis. COMETRAN is used for mapping aerodynamic forces (pressure) from the CFD (Computational Fluid Dynamics) grid to the nodes of the structural FEM (Finite Element Model) and PATRAN is used to interpolate temperatures from CFD grip points to FEM nodes. Typically, the CFD grid is finer than the FEM. Spline3D is used to map the structural deformation onto the CFD surface grid. CSCMDO or FlexMesh perturbs the CFD volume grid to conform to the perturbed CFD surface grid. A FORTRAN code, DEFLECT, that deflect the control surfaces and updates the CFD grid and an Excel spreadsheet, TRIM, that finds the angle of attack and control surface deflections to trim the vehicle were developed.

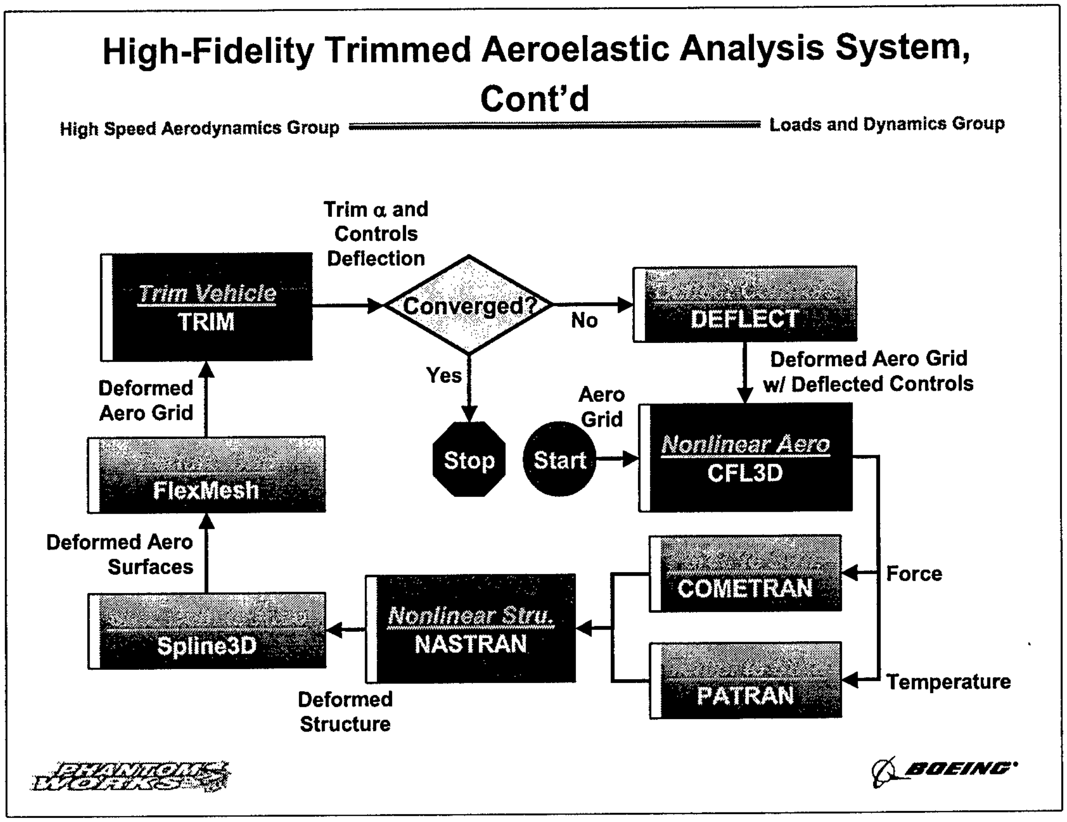
Limited testing of this trimmed aeroelastic analysis system has been successfully completed.



The aeroelastic analysis system is composed of eight modules for the aerodynamics and structures analyses and trimming. A typical global analysis iteration begins with a CFD volume grid, and a complete structural model of the configuration. First, the CFD grid is passed to CFL3D for nonlinear aerodynamic analysis. To hold CPU costs down, the CFD solutions are automatically terminated after a user specified convergence level is reached. The level of convergence needed at each global iteration is not known *a priori*, and some trial-and-error in selecting an optimum level must be expected.

An MSC/NASTRAN finite element model (FEM) is used for the structural analysis. The aerodynamic forces and temperatures are transferred from the aero surface grid to the NASTRAN structural FEM grid using COMETRAN and PATRAN codes, respectively. The loads (pressure as well as thermal) are applied to the NASTRAN model to obtain the structural deflections. NASTRAN has the ability to include the nonlinear changes in structural stiffness as a function of deformation. As the structure deforms under load, the geometric orientation of the FEM changes, therefore its stiffness changes. The NASTRAN structural deflections are interpolated to the aero grid using the Spline3D code.

The deformed aero surface grid and baseline volume grid are passed to the grid perturbation tool, CSCMDO or FlexMesh, to create a CFD volume grid for the deformed geometry. This volume grid is passed to the TRIM module.



In the TRIM module, the sensitivities of forces and pitching moment to control surface deflections are determined by performing CFD analyses on geometries with perturbed control surfaces. Sensitivity to angle of attack is also determined. Using these sensitivities, TRIM determines the angle-of-attack and control surface deflections required to zero-out pitching moment.

The values of angle of attack and control deflections for trim, along with user-selected shape deformation parameters (nose deflection for example) are tested for convergence. If converged the analysis is terminated, else the values of angle of attack and control deflections are passed to DEFLECT. This module deflects the control surfaces and perturbs the CFD volume grid to produce a new deformed grid with deflected control surfaces. The next global iteration begins with the CFD analysis of this perturbed configuration.

This process is completely automated with no user intervention required during the analysis.

CFL3D for Aerodynamic Analysis

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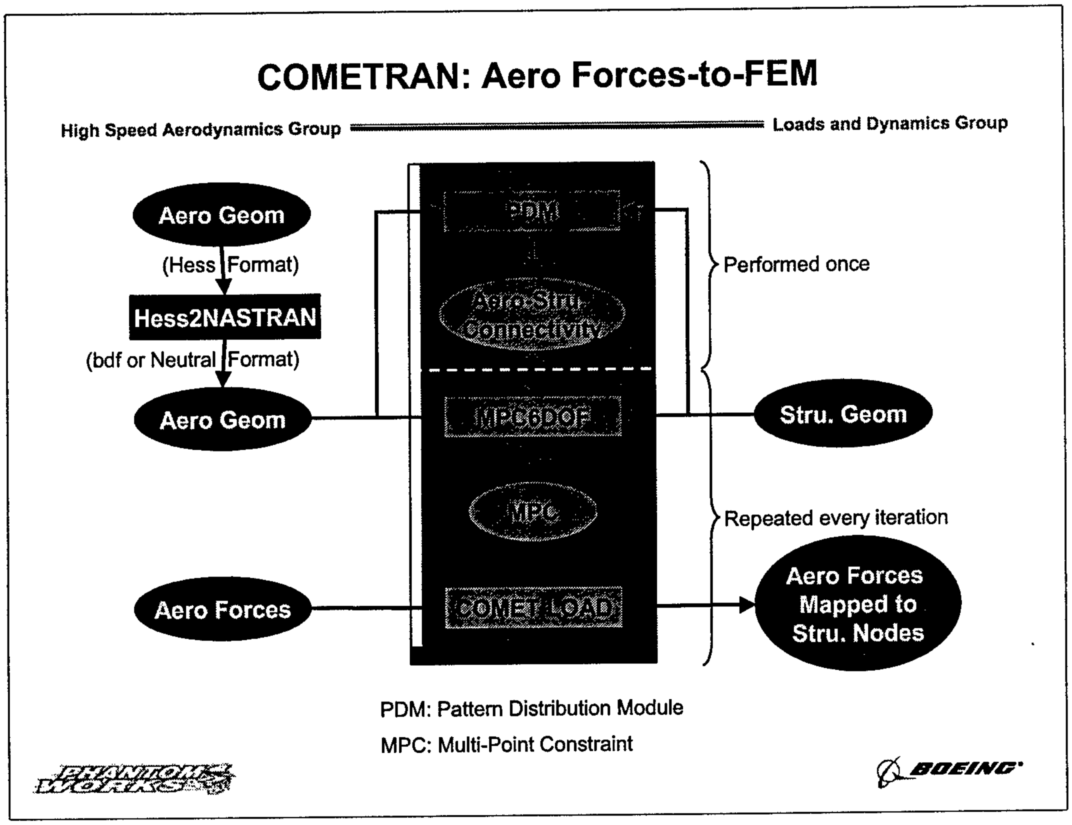
- Developed by NASA Langley Research Center
- Solves unsteady, compressible Euler/Navier-Stokes equations
- Finite-volume formulation
- Upwind discretization
- Choice of turbulence models
- Handles structured multiblock patched or overset grids
- Multigrid acceleration
- MPI protocols for parallel computing

The aerodynamic analysis code is NASA's CFL3D version 6 (CFL3Dv6). It uses a finite-volume upwind formulation to discretize the Euler/Navier-Stokes equations. Both Roe's flux-difference splitting and van Leer's flux-vector splitting discretizations are available. It offers several turbulence models. The multiblock patched or overset grid handling capabilities allow for the analysis of complex configurations. Solution convergence can be accelerated using the multigrid option. It also has a built-in linear structures model for aeroelastic analysis. CFL3D has been successfully used for the aero as well as aeroelastic analysis of numerous industrial applications. CFL3D also has MPI protocols implemented for parallel computing.

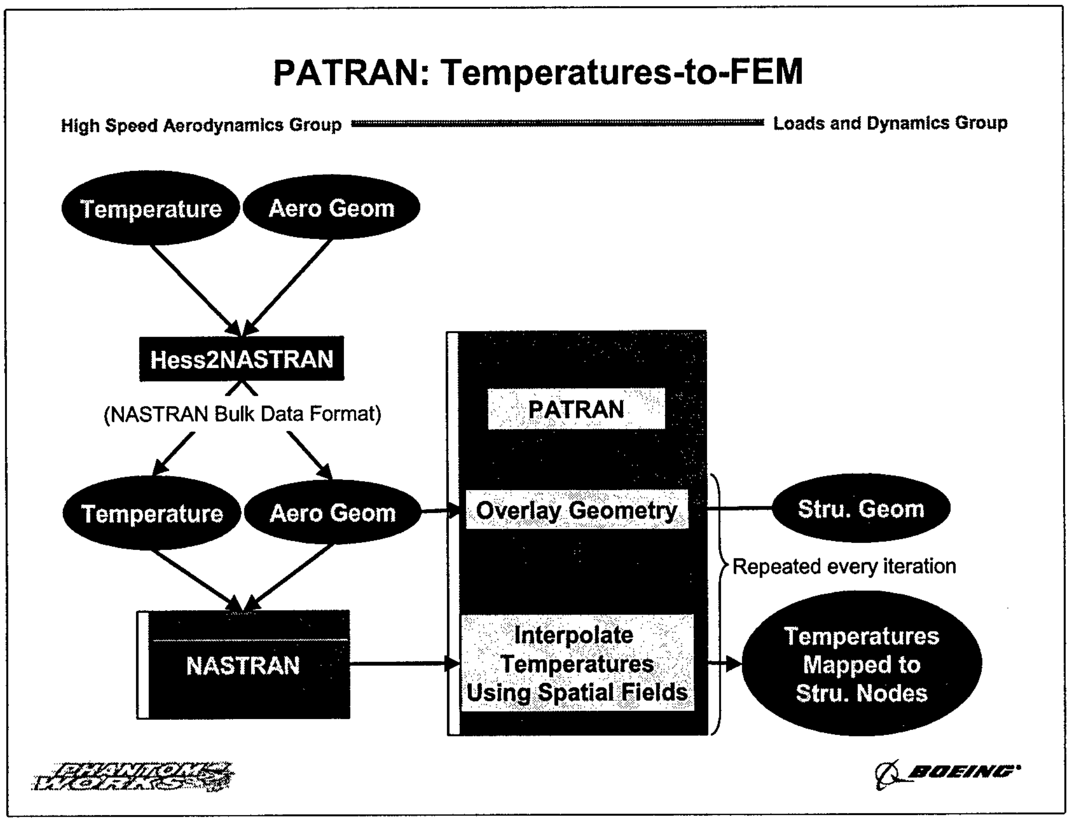
Routines to compute and output aerodynamic forces and temperatures at cell-face centers of the solid surfaces and to output the coordinates of the solid-surface grid points were added to CFL3Dv6. This output is used by the grid perturbation and structures modules.

CFL3D was also modified to check for convergence of lift and pitching moment and terminate execution when user-specified convergence levels are reached.



The aero loads are transferred to the structural model using COMETRAN. The inputs are the geometric definition of the aero grid and corresponding load distribution. First, COMETRAN reads the aero surface grid into the PDM (Pattern Distribution Module) code to establish the Aero-Structural Connectivity. This connectivity can be created by one of several options within PDM. Once this connectivity is established, it is not revised for subsequent load iterations. Next, this connectivity is used by the MPC6DOF (Multi-Point Constraint 6 Degree-Of-Freedom) code to generate the load transformation equations from the aero to structural grid. These equations are in NASTRAN MPC format. The COMET LOAD multiplies these equations by the applied aero loads to transform them and output them as loads on the structural model. The loads on the structural model are output in NASTRAN FORCE card format.

COMETRAN was modified to execute in batch-mode. All the input commands are written to a file which COMETRAN reads and executes without user intervention. A conversion code, Hess2NASTRAN, was developed to convert the aero geometry definition to PATRAN neutral or NASTRAN bulk data format.



The CFL3D analysis computes temperatures at the centroids of the elements on the aerodynamic surface. The aero temperatures are interpolated and transferred to the structural model using MSC/PATRAN. The inputs to PATRAN are the geometric definition of the aero grid, corresponding temperature distribution, and geometric definition of the structural grid. Prior to running PATRAN, NASTRAN is run using the aero geometry and aero temperatures. Since the aero temperatures are at the element centroids, they are applied to the NASTRAN model as element pseudo pressures because this is the only way they can be subsequently interpolated in PATRAN. The NASTRAN run creates a database that contains the temperatures (psuedo pressures) as an applied loads case. PATRAN reads the NASTRAN database of aero temperatures. PATRAN reads the aero and structural geometry in NASTRAN Bulk Data format and overlays the two grids. The aero temperatures are interpolated from the aero grid to the structural grid using the spatial field approach in PATRAN. The temperatures on the structural model are output in NASTRAN TEMP card format.

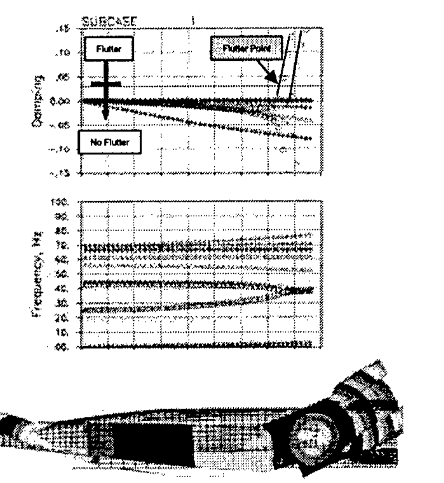
PATRAN executes all of these steps in batch-mode. All the input commands for PATRAN are contained in a session file which PATRAN reads and executes without user intervention.

MSC/NASTRAN for Structural Analysis

High Speed Aerodynamics Group — Loads and Dynamics Group

- Industry Standard Commercial Structural Analysis Code
- Static Stress Analysis
- Thermal Analysis
- Nonlinear Structural Analysis
  - Large Displacement
  - Material Nonlinear
  - Buckling
- Vibration
- Aeroelasticity

Typical NASTRAN Aeroelastic Analysis



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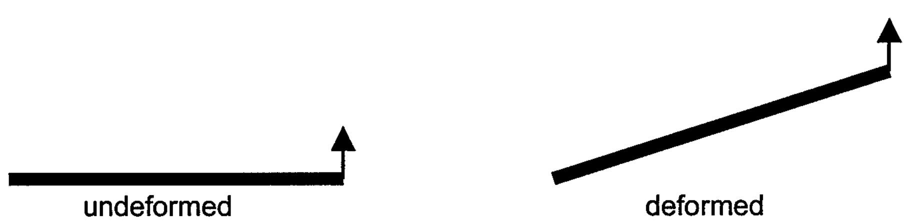
MSC/NASTRAN is a comprehensive finite element structural analysis code. The NASTRAN analysis capabilities include static analysis with nonlinear effects: geometric, material, and temperature. Externally generated nonlinear aero loads are imported into NASTRAN and the converged nonlinear structural deflections are exported to update the shape of the aero model. The primary nonlinear structural effect included in this phase of the process is the geometric nonlinear stiffness effect. The stiffness of the NASTRAN FEM is dependent on the deformed shape of the structure. For example, consider the following structure:



The load applied to the undeformed structure is in a direction purely transverse to the orientation of the structure. Therefore, only the transverse bending stiffness acts to resist the applied load. As the structure deforms, the vertical load now acts at an angle to the structural orientation. Now, there is a component of load acting in the plane of the structure that will be resisted by the in-plane stiffness. This change in effective stiffness as a function of structural deflection and orientation is referred to as the geometric nonlinear stiffness. This system can also model certain other nonlinearities, for example, nonlinearity due to aerodynamic follower forces.

Spline3D: FEM-to-Aero Transformation

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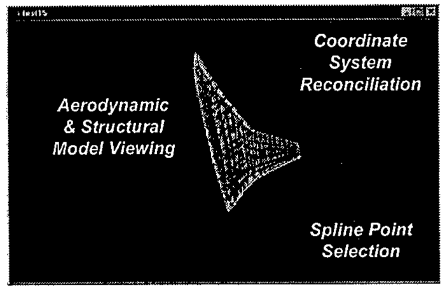
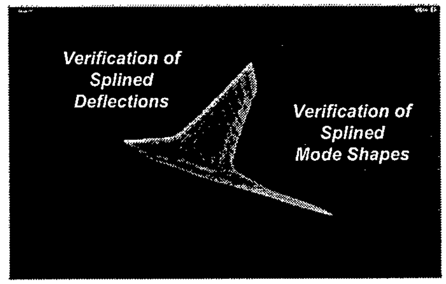
- In-House C/C++ code
- Maps structural deflections to aerodynamic grids
- Several splining options
- Generates splined deflections and spline matrix
- Interactive GUI for set-up of splines
- Can be run in batch mode for loosely-coupled aeroelastic analysis





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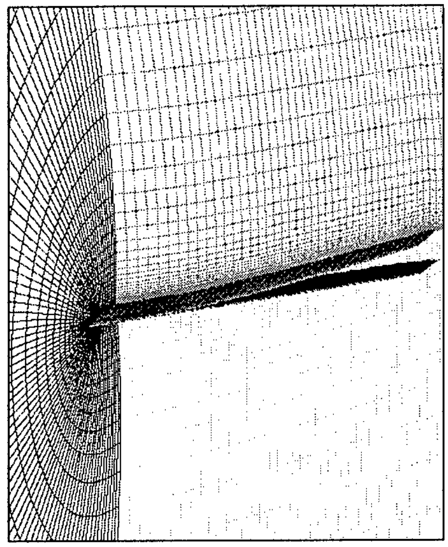
The Spline3D code was specifically developed for the challenges of computational aeroelasticity. It contains an interactive Graphical User Interface so the user can immediately see which structural nodes are splined to which aerodynamic grid points, visualize the deflections, and get an immediate visual verification of the spline quality. In its original form, it was used only to spline vibration mode shapes from a structural (finite element) model to a computational (CFD) surface grid.

The main modification made to Spline3D for this contract was the addition of a non-interactive (batch) mode. This required modifications to the user interface portions of the code to allow file-driven operations rather than mouse-driven operations. These modifications have been completed and the code has been demonstrated in the overall aeroelastic analysis process.

Grid Perturbation using CSCMDO

High Speed Aerodynamics Group — Loads and Dynamics Group

- Licensed by NASA Langley
- System is very robust and has been successfully used for complex configurations
- Output grids are of high quality with minimal CPU demands
- Portable
- Developing input deck can be labor intensive for complex configurations



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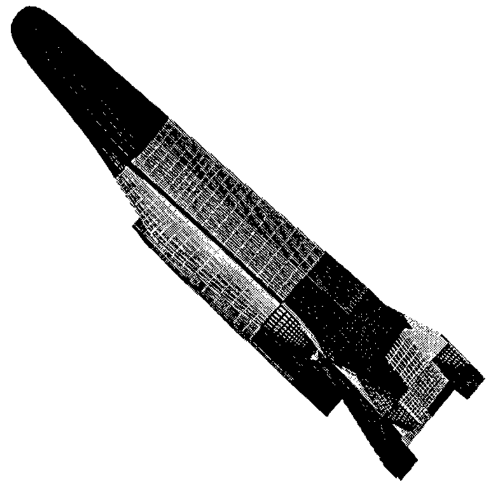
New aero grid for the structurally deformed configuration is generated by perturbing the baseline aero grid using CSCMDO. Freely licensed by NASA Langley Research Center, it produces high quality perturbed grids with low computational overhead. However, creating an input deck for complex configurations with many (>>10) grid block is labor intensive.

Grid Perturbation using FlexMesh

High Speed Aerodynamics Group — Loads and Dynamics Group

- Developed In-house
- System is generally robust and has been successfully used for complex configurations
- Output grids are of reasonable quality with minimal CPU demands
- Portable
- Uses the flow solver (CFL3D) input deck



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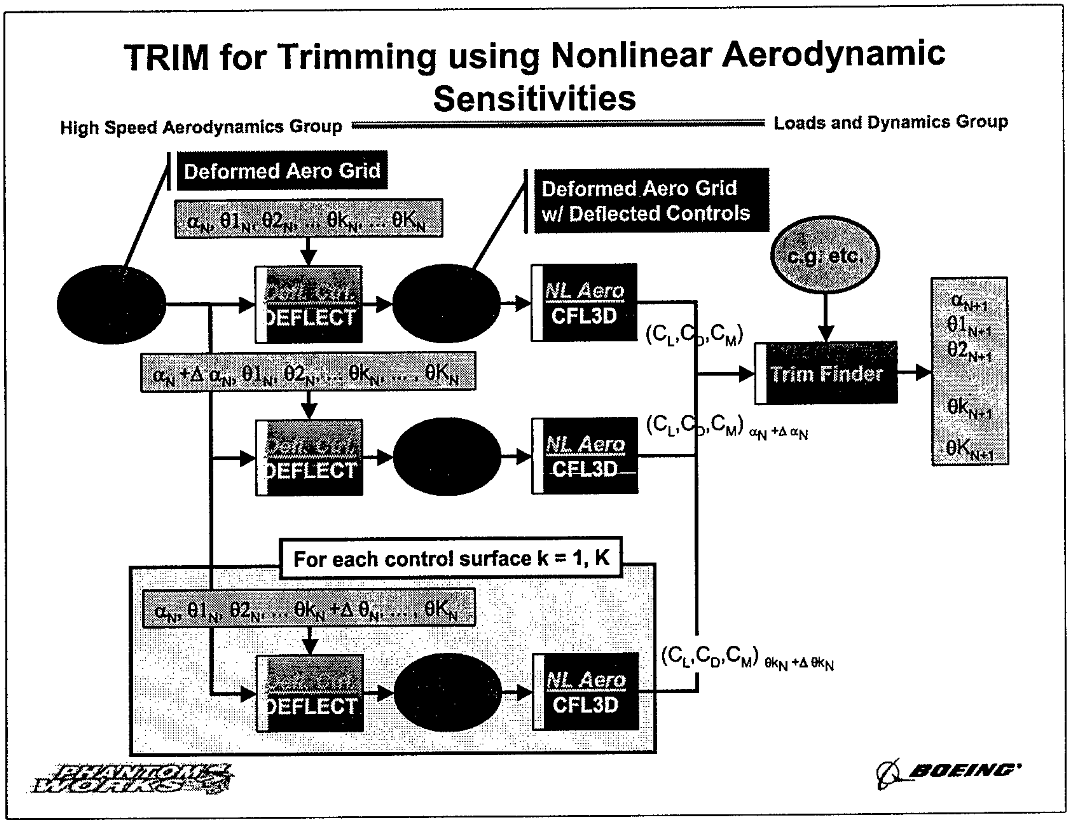
Although CSCMDO produces high quality perturbed grids, an input deck for complex configurations with many (>>10) grid block is very labor intensive. For example, a CSCMDO input file for a 100-block CFD grid could take more than a month to create. Hence, an alternate grid perturbation code, FlexMesh, is also included as part of this analysis system. The primary advantage of FlexMesh is that it uses the same input deck that the CFL3D flow solver uses. The quality of the grid it produces is considered to be reasonably good for the type of applications considered here.



TRIM receives the aeroelastically deformed CFD grid. First, a CFD analysis of this "baseline" configuration is performed. Next, a CFD analysis is done with the angle of attack perturbed to obtain sensitivities of forces and moments. Then CFD analyses are performed with each of the control surfaces perturbed in order to compute their respective sensitivities. Sensitivities are determined using finite differences. Using these sensitivities and externally supplied center-of-gravity location, the values of angle of attack and control surface deflections that trim the vehicle are determined.

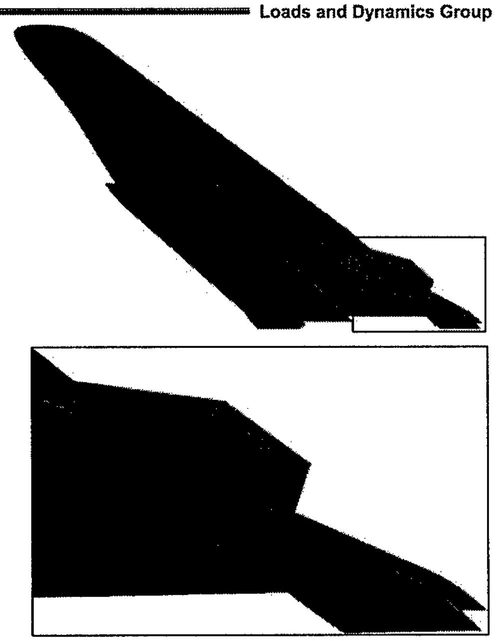
TRIM is computationally the most demanding module in this analysis system. For a vehicle with K control surfaces, K+2 CFD analyses are required, per global iteration, to find the trim point. The hypersonic vehicle used in this demonstration, has only one control surface. Therefore 3 CFD analyses are required to trim the vehicle. Note that one more CFD analysis is requited in the main loop of the analysis process.

For hypersonic air-breathing vehicles, propulsion is a major contributor to pitching moment. In this prototype, this contribution has been ignored. A propulsion analysis module is necessary to model the propulsive forces and moment. Once such a module is available, integrating it into this system is trivial.

Deflect Control Surfaces using DEFLECT

High Speed Aerodynamics Group — Loads and Dynamics Group

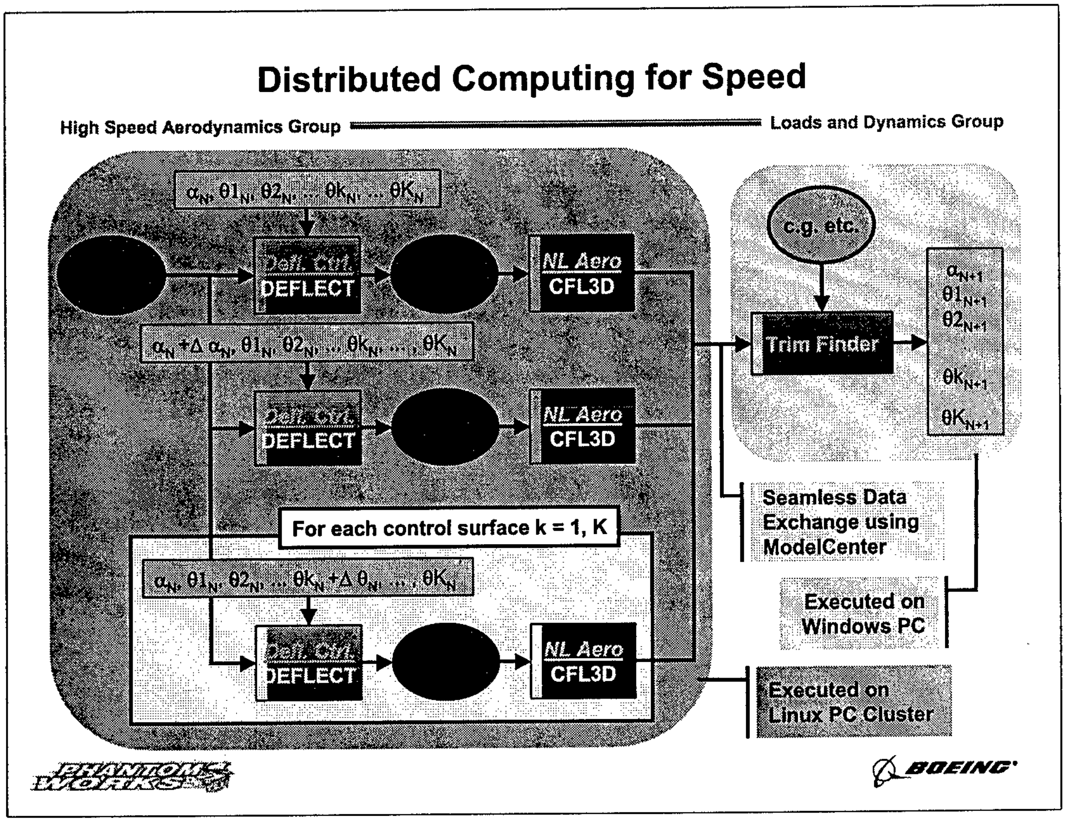
- Developed in-house
- Easy to use
- Minimal input setup
- Fast control surface deflection and volume grid perturbation
- Large control surface deflections
- Reasonably robust
- Skewed cells near body junction, but perturbed grids are generally of acceptable quality



PHANTOM WORKS — BOEING

During the trimmed aeroelastic analysis, the control surfaces have to be deflected many times and the CFD grid perturbed. An in-house developed code, DEFLECT, was used for this purpose. Simplicity and ease of use are two of the main characteristics of this method, which requires only minimal inputs: a series of points describing the control volume enclosing the surface to be deflected, two points defining the axis of rotation, the deflection angle, and the names of the input and output grid files. The volume grid outside the control volume remains un-perturbed, while the grid inside undergoes a rigid-body rotation about the axis. Speed is the other major advantage of this approach. It takes only a few seconds of CPU time to deflect the control surfaces and update the volume grid.

However, since no smoothing is performed, large deflections can have a negative impact on the quality of the perturbed grid or even result in negative volumes. Nevertheless, once appropriate control volumes for control surface rotation have been defined, it is generally possible to achieve large control surface deflections without producing negative volumes and without significantly affecting the stability of the flow solver due to degradation of grid quality.



CFD analysis is computationally the most expensive process of this trimmed aeroelastic analysis system. CFD analyses accounts for over 90% of the CPU time used in every global iteration. For a vehicle with K control surfaces, K+2 CFD analyses are required, per global iteration, to find the trim point. The hypersonic vehicle used in this demonstration, has only one control surface. Therefore, 3 CFD analyses are required to trim the vehicle. Thus, TRIM is the computationally the most demanding module in this analysis system.

In order to speed-up the trimming process, TRIM is executed on a Linux PC-cluster. Since CFL3D has MPI protocols, the CFD analyses are executed in the parallel mode. Depending on the availability of processors, significant speed-up of the overall analysis can be achieved. All the other modules are typically executed on a workstation. All these modules combined need less than 10% of the total CPU time.

Seamless data exchange between modules is facilitated by Phoenix Integration's ModelCenter and AnalysisServer.

Distributed Computing using ModelCenter

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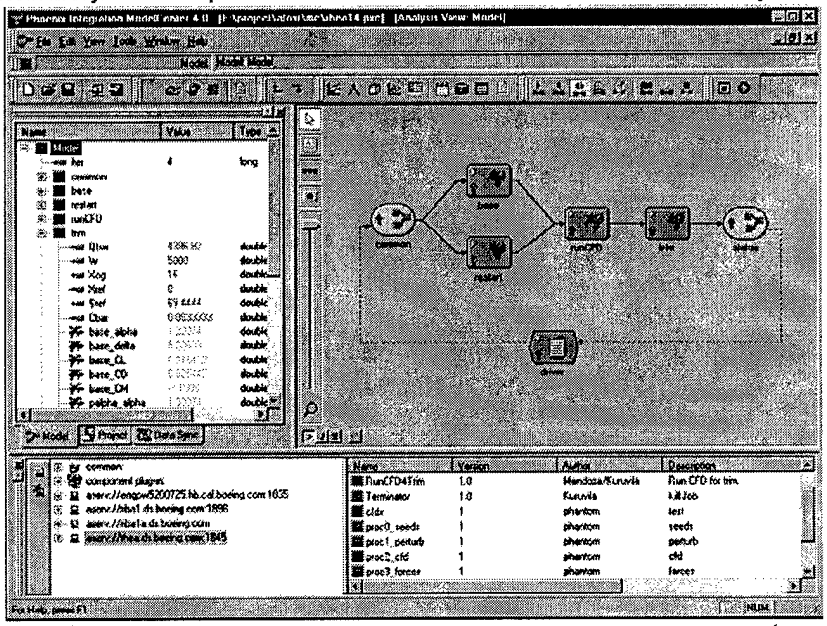
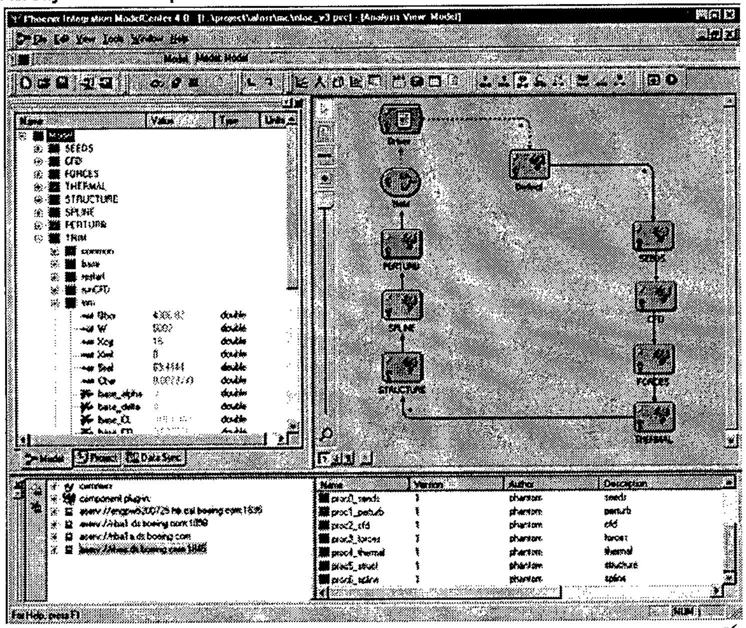


Shown here is the TRIM module in Phoenix Integration's ModelCenter environment. Use of this software integration tool, allows TRIM to be executed on a LINUX PC-cluster. By using multiple processors, the CFD solutions required to compute sensitivities are obtained fairly quickly. The resulting data is passed automatically to the downstream module. While this process can be accomplished using UNIX shell scripts, developing and debugging scripts that can communicate across platforms is very time consuming. ModelCenter offers a very simple and easy means for software integration and an easy-to-use Graphical User Interface for launching and monitoring of the analyses processes.

Model Center Model of the Complete Analysis System

High Speed Aerodynamics Group — Loads and Dynamics Group



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BOEING

The entire trimmed aeroelastic analysis system, wrapped using ModelCenter is shown here. Using ModelCenter, the modules can be distributed on suitable platforms across the network. In this process, the computationally intense CFD analysis process is executed on a 96-processor Linux PC-Cluster while all the other modules are hosted on a 8-processor Origin 2000 except the trim finder which is executed on a Windows PC.

All data transfers among modules are handled by ModelCenter and the details are transparent to the user. A driver that can launch, monitor and terminate the process can be easily added. As the analysis progresses, the intermediate results can be viewed and plotted.

These wrapped modules can be easily reused to build other processes.

Since ModelCenter is a commercial product, a license is required to use it.

Test Cases

High Speed Aerodynamics Group — Loads and Dynamics Group

- AGARD 445.6 Wing
- HSR FSM Wing/Body
- Air-Breathing Hypersonic Vehicle

A series of tests of this high-fidelity aeroelastic system were performed using increasingly complex configurations. The aeroelastic analysis without trim and rigid-body trim processes were well tested. The trimmed aeroelastic analysis process underwent only limited testing. Due to the high computational resource requirement of the complete process and due to unanticipated shut down of the PC-cluster for upgrades, a converged trimmed aeroelastic solution was not obtained.

Test Using AGARD 445.6 Wing

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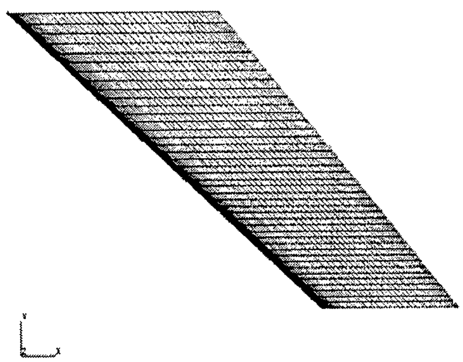
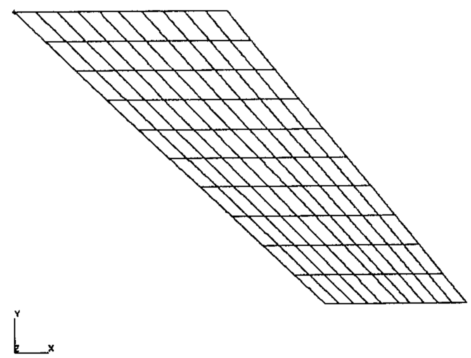
Tested interaction of CSCMDO, CFL3D, COMETRAN, NASTRAN, & Spline3D

Aero Grid



Structural FEM



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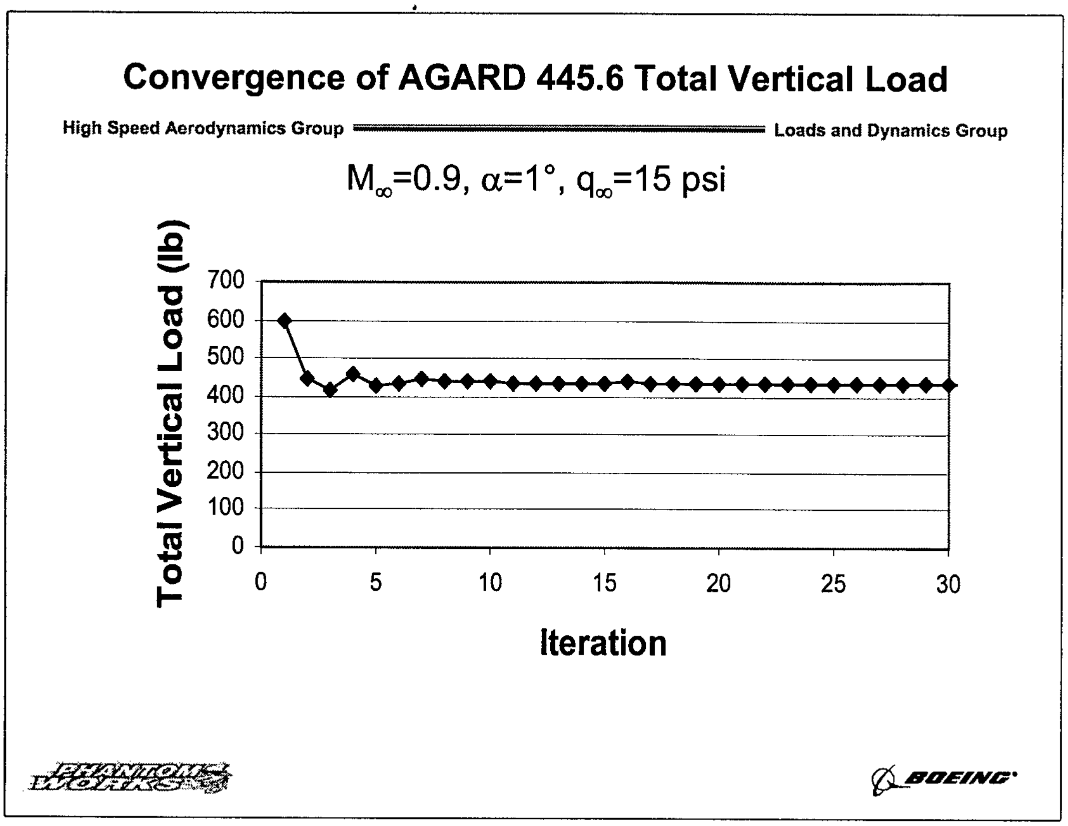
In this test case, using the AGARD 445.6 wing, the interaction of all the modules of the nonlinear aeroelastic analysis process, except the PATRAN temperature interpolation module, was tested. The aero grid and the structural NASTRAN FEM grid are shown. The structural NASTRAN FEM grid is coarser than the aero grid, which is usually the case for most aeroelastic models.



This chart shows the history of total vertical load at M_∞=0.9 and α=1.0°. The total vertical load converges to a constant value in less than 15 iterations. The aerodynamic analysis was performed in the Euler (inviscid) mode.

Convergence of AGARD 445.6 Wing Tip Deflection

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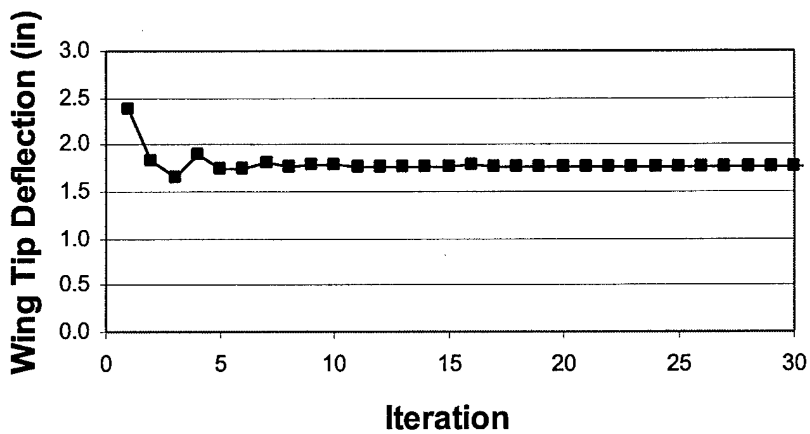
M_∞=0.9, α=1°, q_∞=15 psi



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The convergence of the wing tip deflection at M_∞=0.9 and α=1.0° is shown. The wing tip deflection converges to a constant value.

Computer Resources for AGARD 445.6

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- Memory
  - Less than 200 MB at any time
- CPU Time
  - 65% CFL3D
  - 10% COMETRAN
  - 20% NASTRAN
  - 5% Spline3D
- File I/O overhead
  - 10% of the CPU time

Computational resource requirements will be proportional to the size and complexity of the analytic models. This simple model which has 500,000 grid points did not require a great deal of computational resources. The relative amounts of computation for the various steps of the analysis process were:

Memory: CFL3D required about 160 MB of memory while CSCMDO needed only 30 MB. The small memory models of COMETRAN and NASTRAN use 8 MB of memory, and the large memory models use 32 or 64 MB. Since sufficient memory was available, the 64MB model was used in this exercise.

CPU time: For this test problem, each global iteration required about 1 hour and 30 minutes of CPU time. Approximately 65% of the time was used by CFL3D, 10% by COMETRAN, 20% by NASTRAN and 5% by Spline3D. CPU time needed for grid perturbation using CSCMDO was negligible.

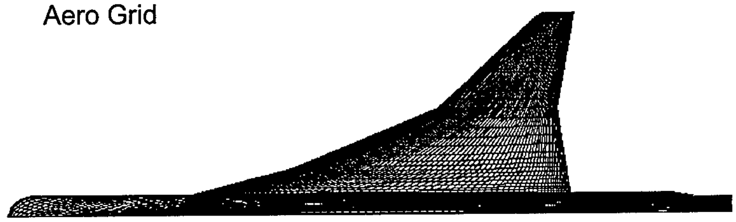
File I/O overhead: A rough estimate indicates that file I/O consumes less than 10% of the total time.

Test using HSR Flexible Semispan Model (FSM)

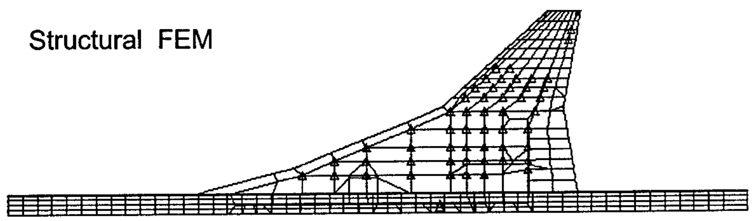
High Speed Aerodynamics Group ═══════ **Loads and Dynamics Group**

Tested interaction of CSCMDO, CFL3D, COMETRAN, NASTRAN, & Spline3D

Aero Grid



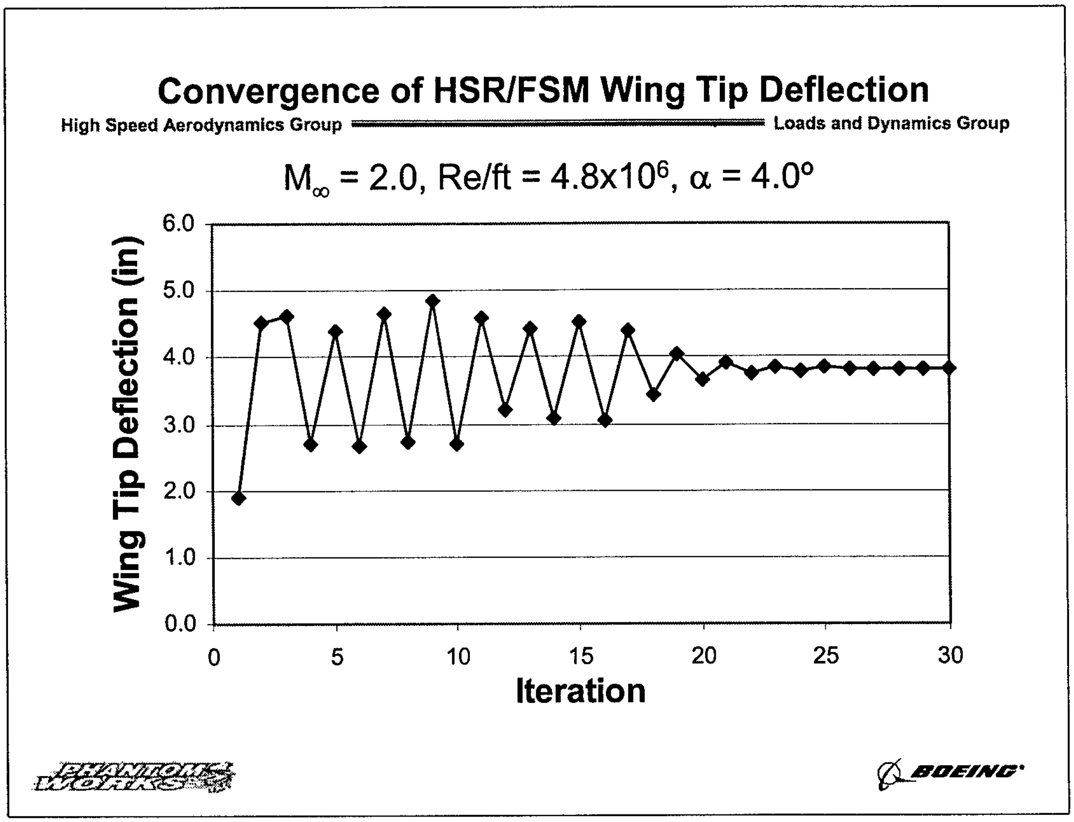
Structural FEM



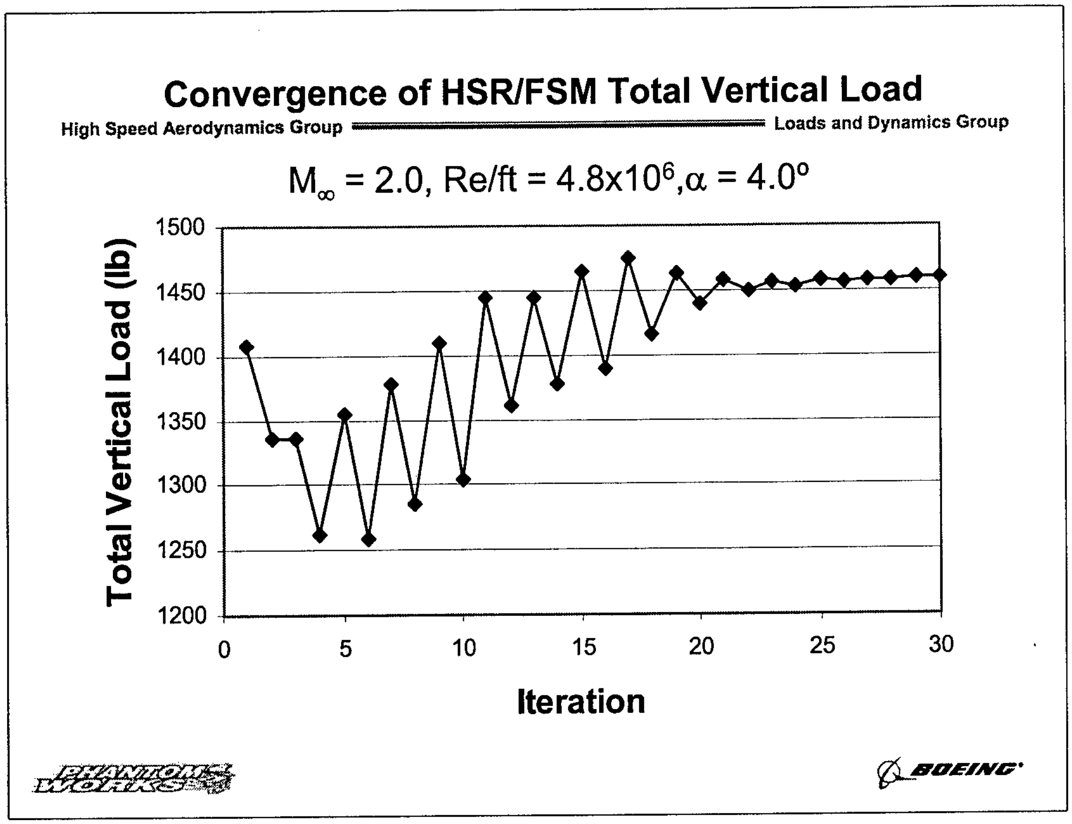
PHANTOM WORKS

BOEING

In this case, the nonlinear aeroelasticity analysis system was tested using the High Speed Research (HSR) Flexible Semispan Model (FSM) wing/body model. The aero grid and the structural NASTRAN FEM grid are shown. This model was created as part of the Aeroelaticiy Wind Tunnel Models program during the NASA/Industry HSR program. The structural NASTRAN FEM grid is coarser than the aero grid, which is usually the case for most aeroelastic models. Here, the aerodynamic analysis was performed in the Navier-Stokes (viscous) mode.



The convergence of the HSR/FSM wing tip deflection, for the case with M_∞=2.0 and α=4.0° is shown here. After 15 iterations it was noted that the CFD sub-iteration was not reducing the residual sufficiently. This led to non-convergence of the global problem. After the 15th iteration, the number of iteration within CFL3D was increased, leading to convergence toward a constant deflection. A "smarter" convergence monitoring routine was added to CFL3D, and it was exercised in the later tests reducing the number of global iterations required to obtain a converged solution.



This chart shows the history of total applied vertical load on the HSR/FSM for the case with M_∞=2.0 and α=4.0°. Once again, after modifying the convergence parameters within CFL3D after the 15th iteration, total vertical load converged to a constant value.

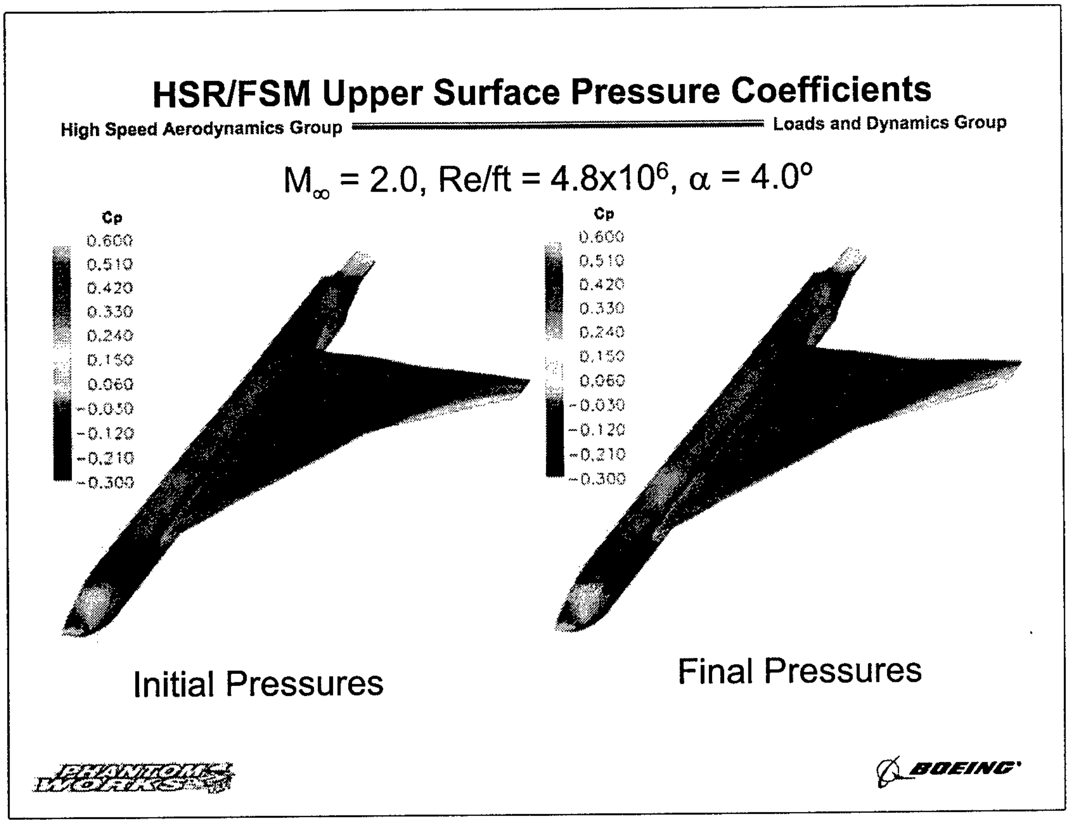
HSR/FSM Wing Deflection

High Speed Aerodynamics Group — Loads and Dynamics Group

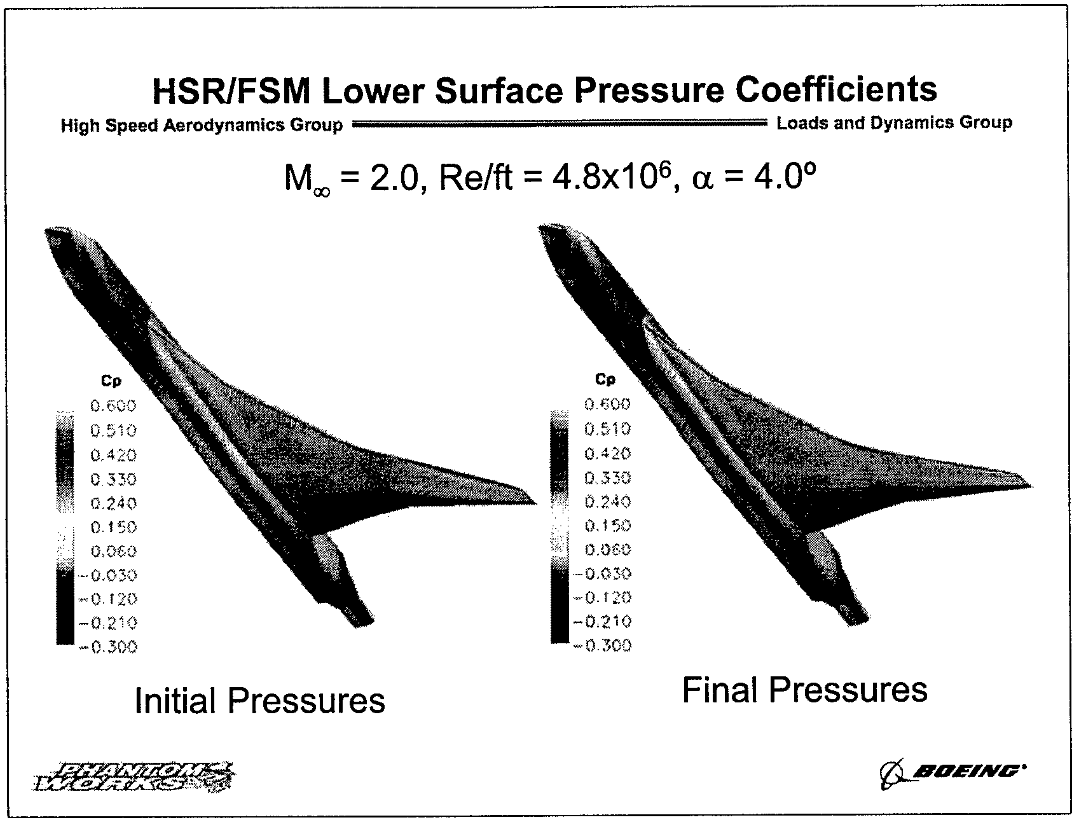
$M_\infty = 2.0$, $Re/ft = 4.8 \times 10^6$, $\alpha = 4.0°$

(Deflections are not exaggerated)

Wing deflections for the initial and final iterations are shown. This problem setup did not induce overly large deflections. However, note that the wing does not merely deform in shear as in many linear applications. This distinction will become more apparent in applications with more significant deformations.



Upper surface pressure coefficients on the initial undeformed and final deformed FSM model test case are shown. Loads were kept fairly low during this test case, so while the deflections and changes in pressure can be seen, they are not very large. However, the deformed wing does have less vertical loading on the outboard panel as expected due to the washing-in of the wing twist (note the increased pressures on the outer panel in the deformed geometry).



Lower surface pressure coefficients on the initial undeformed and final deformed FSM model test case are shown. The deformed wing does have less vertical loading on the outboard panel as expected due to the washing-in of the wing twist (note the lower pressures on the outer panel in the deformed geometry).

Computer Resources for HSR/FSM

High Speed Aerodynamics Group — Loads and Dynamics Group

- Memory
  - Less than 400 MB at any time
- CPU Time
  - 93% CFL3D
  - 2% COMETRAN
  - 4% NASTRAN
  - 1% Spline3D
- File I/O overhead
  - 2% of the CPU time

PHANTOM WORKS — BOEING

This model, which has about 1×10^6 grid points, required significantly more resources than the first test problem. The relative amounts of computation for the various steps of the analysis process were:

Memory: CFL3D required about 320 MB of memory while CSCMDO needed only 30 MB. The small memory models of COMETRAN and NASTRAN use 8 MB of memory, and the large memory models use 32 or 64 MB. Since sufficient memory was available, the 64MB model was used in this exercise.

CPU time: For this test problem, each global iteration required about 7 hours of CPU time. Approximately 93% of the time was used by CFL3D, 2% by COMETRAN, 4% by NASTRAN and 1% by Spline3D. CPU time needed for grid perturbation using CSCMDO was negligible.

File I/O overhead: A rough estimate indicates that file I/O consumed less than 2% of the total time.

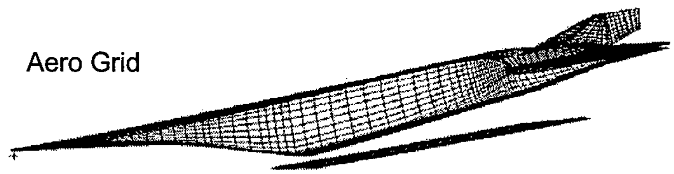
The significant increase in CPU time for the CFD analysis was due to the use of Navier-Stokes analysis and the increase in number of iterations that were necessary for the CFD iterations to converge.

Test using Hypersonic Vehicle model

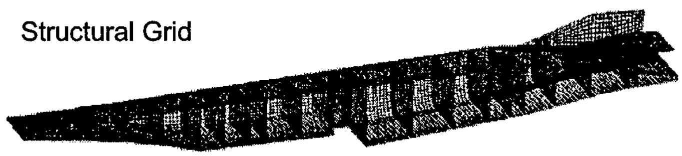
High Speed Aerodynamics Group — Loads and Dynamics Group

Tested including nonlinear deflection and thermal effects

Aero Grid



Structural Grid



PHANTOM WORKS

BOEING

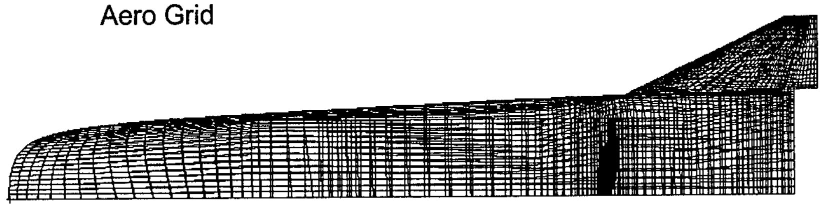
In this case, the complete nonlinear aeroelasticity analysis system, including temperature effect, was tested using a hypersonic air-breathing vehicle model. The aero grid and the structural NASTRAN FEM grid are shown. The structural model was created as part of another project. The structural NASTRAN FEM grid is a fine grid consisting of 15221 grid points and 15592 elements. The structural model includes internal structural bulkheads. The structural properties for the FEM do not accurately represent the actual stiffness; arbitrary sizing was adequate to test the nonlinear deflection and temperature analysis process. Here, the aerodynamic analysis was performed in the Euler (inviscid) mode.

Test using Hypersonic Air-Breathing Vehicle

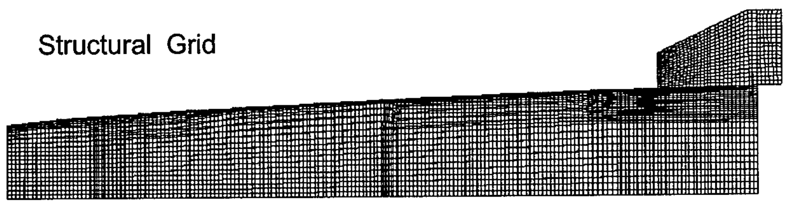
High Speed Aerodynamics Group — Loads and Dynamics Group

Tested including nonlinear deflection and thermal effects

Aero Grid

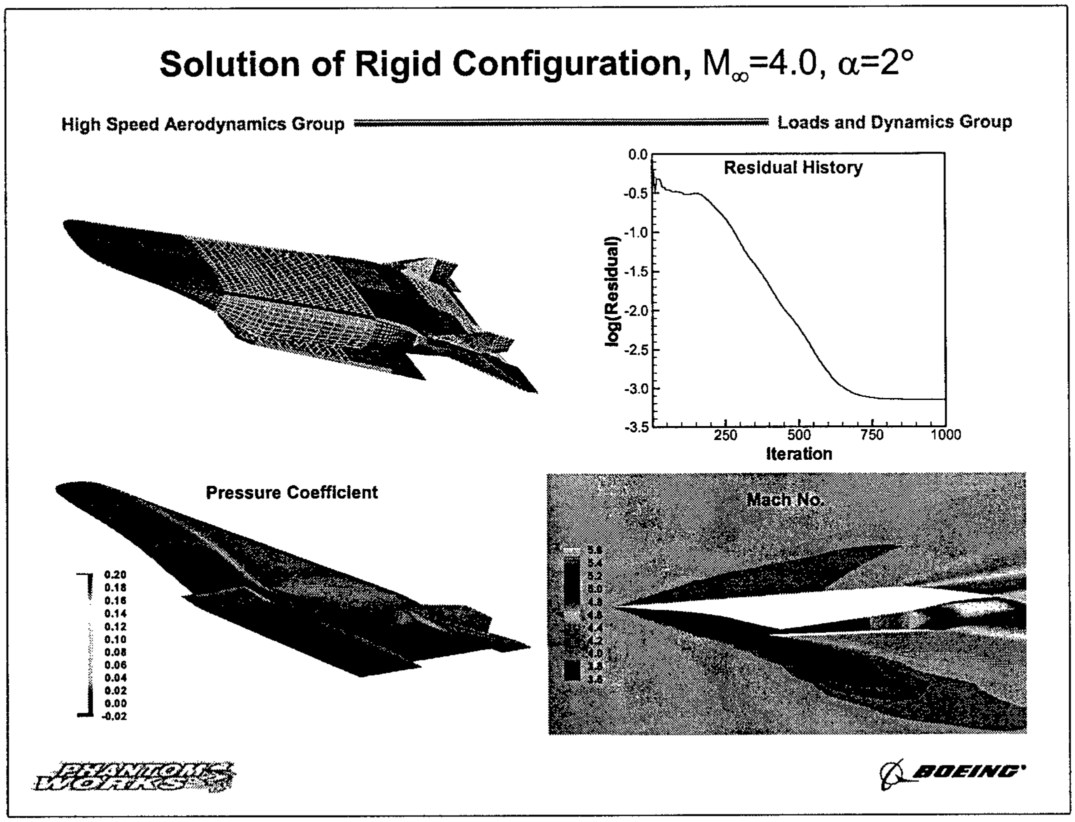


Structural Grid



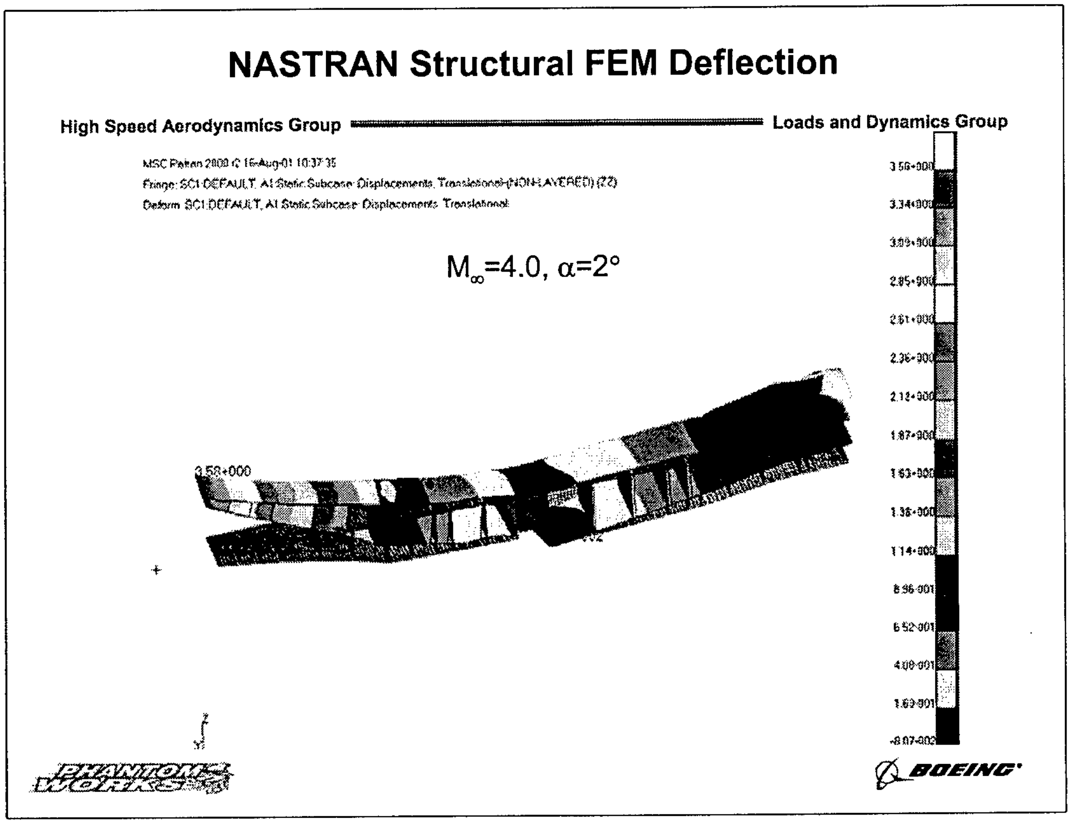
PHANTOM WORKS — BOEING

Top views of the aero and the structural grids are shown.



The solution of the baseline configuration at M_∞=2 and α=2° is shown. The CFD grid for the half-geometry has 124 point matched blocks and about 373,000 points. Since the appropriate engine inlet and exit conditions were not known, the propulsion flow-path was modeled as flow-through. In order to prevent the flow from choking, the side wall of the engine were removed. Since this is an exercise in testing the aeroelastic analysis system, these simplifications are not considered to be unreasonable.

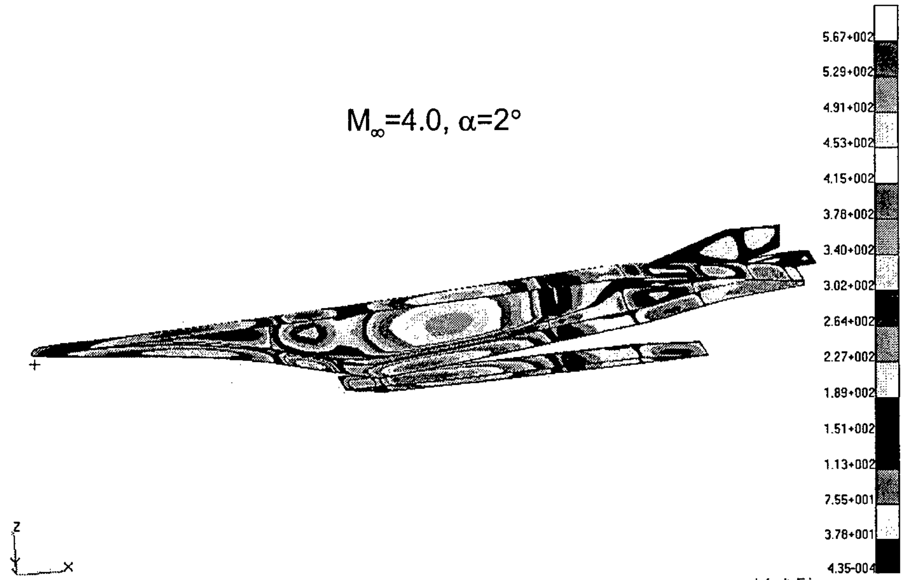
CFL3D was executed in the parallel mode on an Origin-2000 using 3 processors. About 5 hours of wall-clock time was required to perform 1000 iterations of Euler analysis.



A contour plot of the converged deflection the hypersonic vehicle Mach 4 case is shown here. The structural model was analyzed with a symmetric boundary condition applied at the centerline of the half model. Rigid body motions were restrained by holding the model fixed near the engine inlet. The plot shows that the overall deflection is primarily a nose up, tail up distribution.

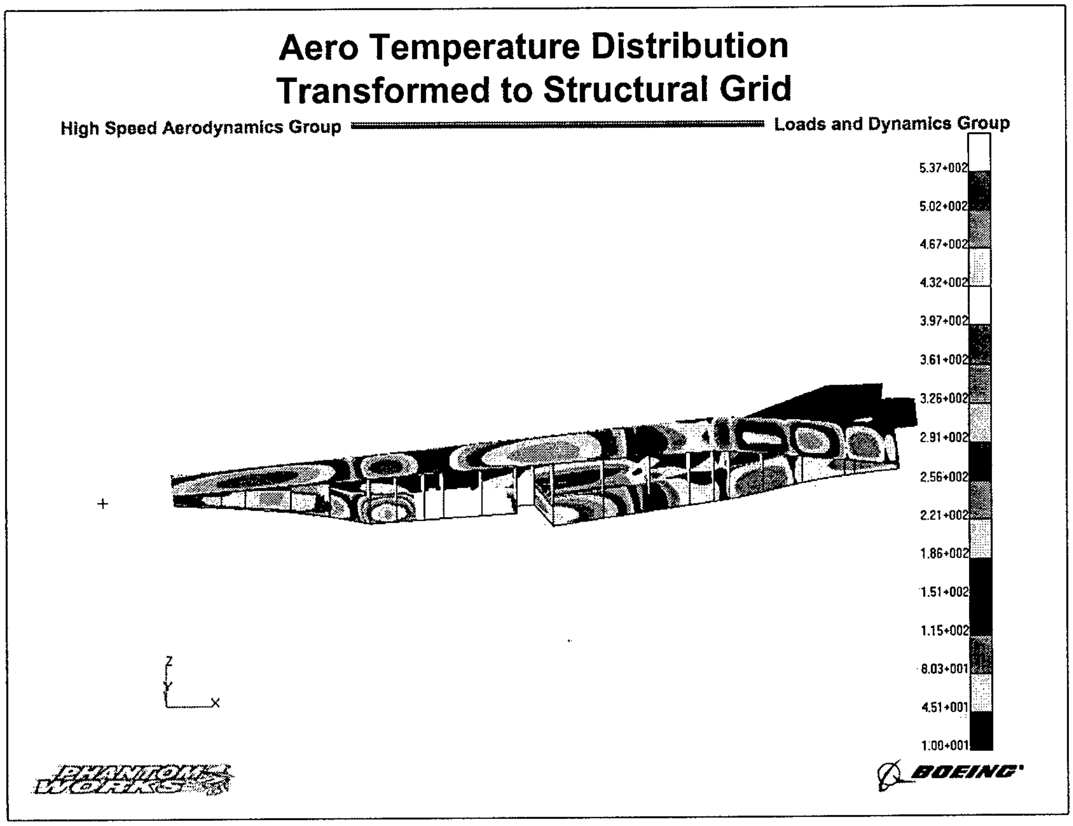
PATRAN Aero Temperature Distribution

High Speed Aerodynamics Group — **Loads and Dynamics Group**

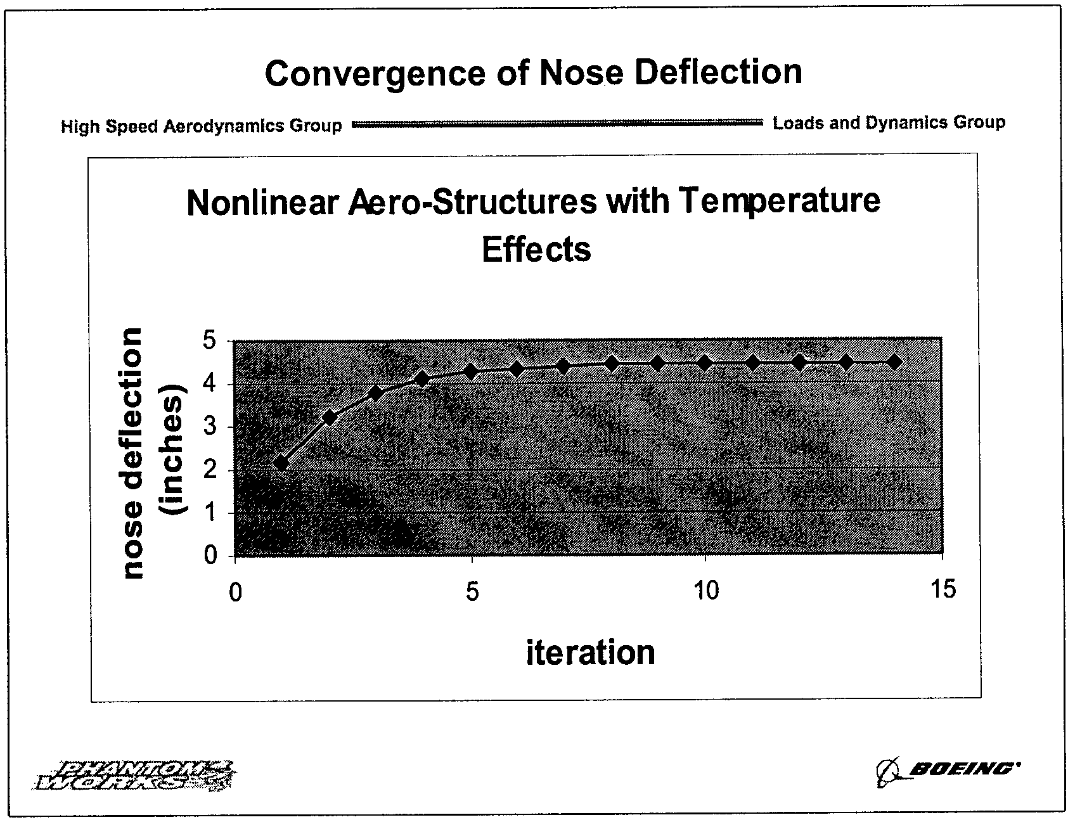


PHANTOM WORKS — BOEING

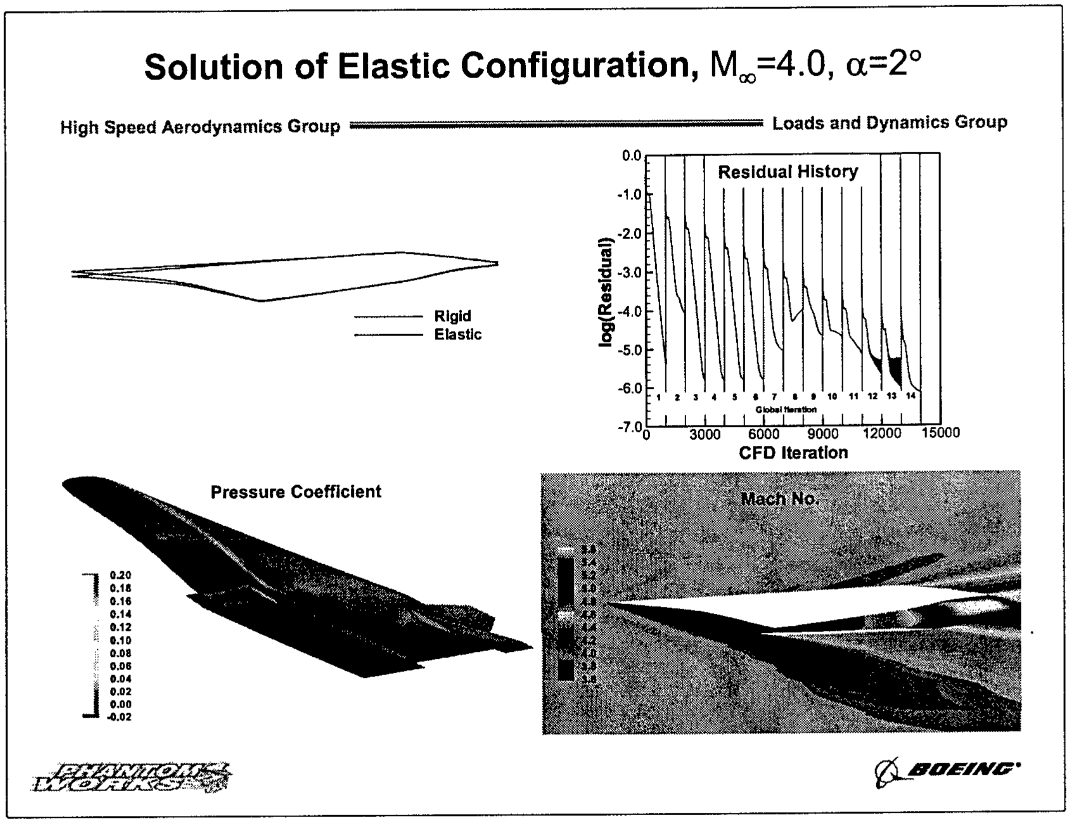
A contour plot of the converged temperature distribution for the the hypersonic vehicle Mach 4 case is shown here. MSC/PATRAN was used to interpolate this distribution from the aerodynamic grid to the structural grid for each iteration.



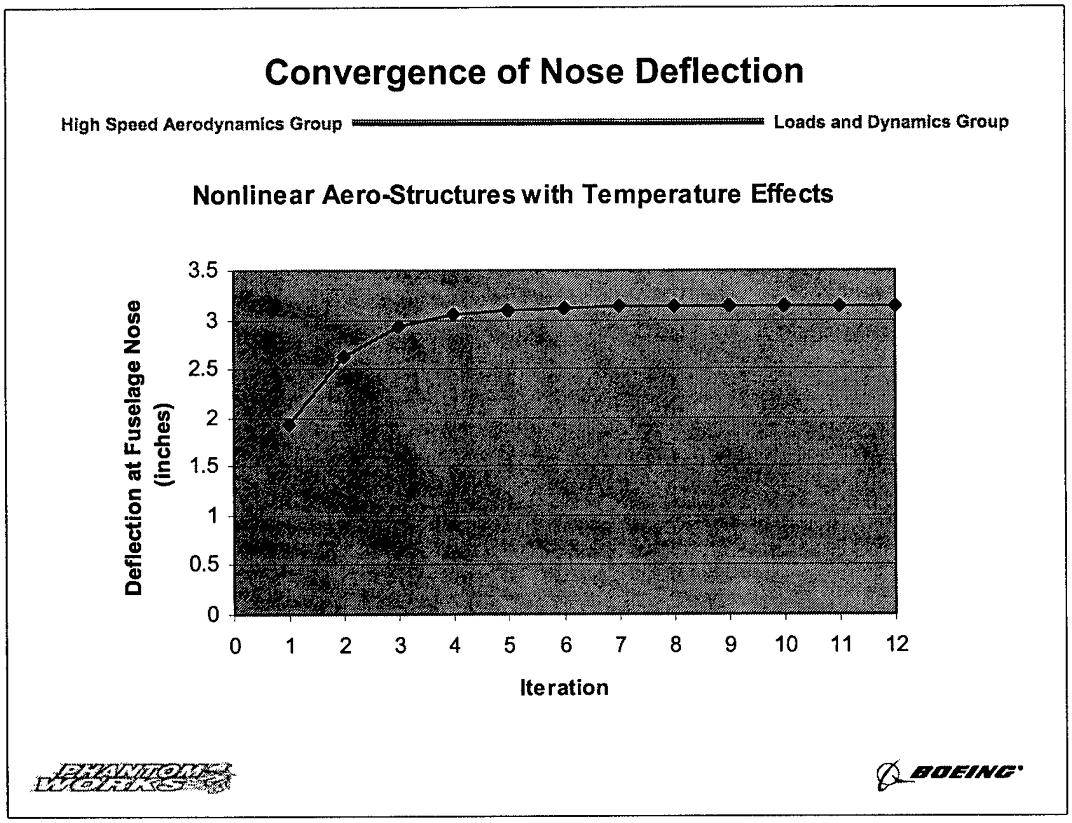
A contour plot of the converged normalized temperature distribution interpolated to the structural model for the Mach 4 case is shown here. MSC/PATRAN was used to interpolate the temperature distribution from the aerodynamic grid to the structural grid for each iteration. Regions on the model that are white have no temperatures interpolated to them. This is because the physical locations of the aero and structural model geometries are too far apart in these regions. For example, the area on the lower fuselage just forward of the engine inlet has no interpolated temperature. Similarly, the internal structural bulkheads are not included in the aerodynamic model, therefore there is no temperature interpolation for those areas. By examining the aero and structural models in these areas, it is obvious that the geometries are different. It is common practice to have regions of a structural model different from an aerodynamic model. However, this example demonstrates that the geometries should be close in order for the temperature interpolation to be reasonable. The test models are different because existing models were used. For future studies, models should be created with similar geometry in areas where temperature effects are important.



The convergence of the deflection at the nose of the fuselage for the hypersonic vehicle is shown here. In less than 10 iteration, the aeroelastic deformation of the vehicle reached a constant state.



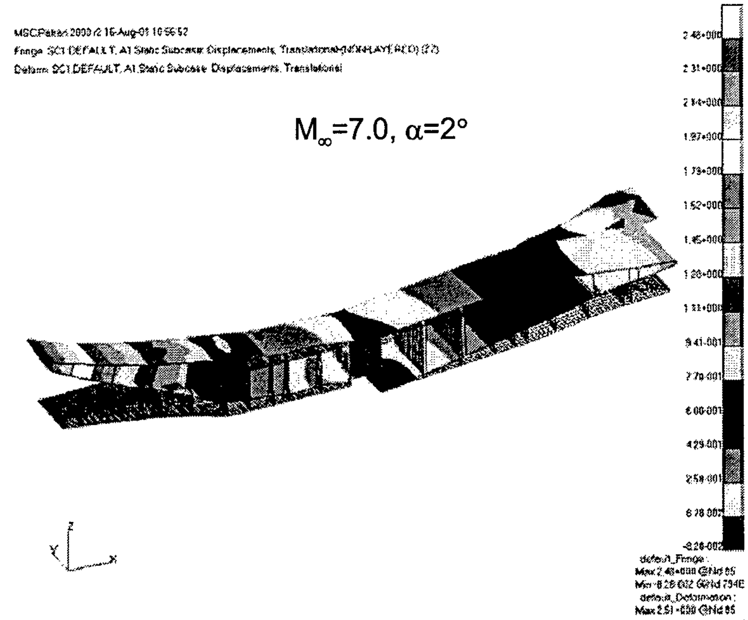
The flow solution of the elastic configuration at M_∞=2 and α=2° is shown. Increase in pressure near the lower surface nose of the fuselage.



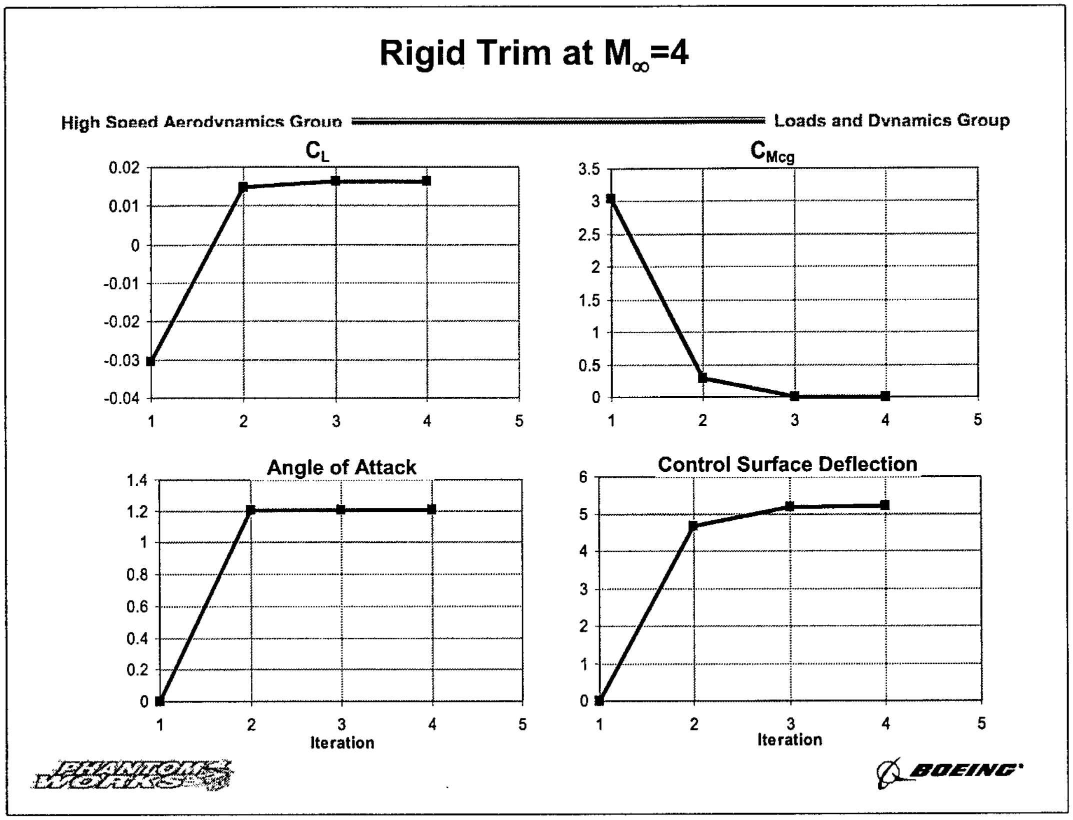
The convergence of the deflection at the nose of the fuselage for the hypersonic vehicle, for the Mach 7, case is shown here. The aeroelastic deformation reached a constant state in about 8 iterations.

NASTRAN Structural FEM Deflection

High Speed Aerodynamics Group — **Loads and Dynamics Group**



A contour plot of the converged deflection the hypersonic vehicle Mach 7 case is shown here. The structural model was analyzed with a symmetric boundary condition applied at the centerline of the half model. Rigid body motions were restrained by holding the model fixed near the engine inlet. The plot shows that the overall deflection is primarily a nose up, tail up distribution. The nose deflection for this case is about 3 inches.



Results of trimming a rigid hypersonic vehicle are shown here. In this case, the control surface is an all moving horizontal tail. Here, each trim solution required 3 CFD solutions to compute the necessary sensitivities. In order to obtain CFD solutions rapidly, TRIM was executed on a Linux PC-Cluster via ModelCenter. A routine that monitors convergence and terminates execution, when a predetermined level of convergence is achieved, was used to reduce the overall CFL3D execution time.

The figure shows that the vehicle trimmed in about 2 iterations. In this demonstration, the control surface is warped instead of deflected as a solid body. Solid body rotation requires additional coding to maintain the neighboring grid topology. When used in the aeroelastic analysis system, TRIM is executed only once every global iteration. Fully trimmed solution is attained as the structural deformation also converges.

Note that the propulsive forces and moments were excluded from this demonstration. A suitable propulsion module can be easily added to this process.

Future Direction

High Speed Aerodynamics Group — Loads and Dynamics Group

- Significantly reduce CFD analysis time
- Use unstructured CFD for easy deflection of control surfaces
- Develop unstructured grid perturbation tool
- Include optimization to maintain performance (L/D) or minimize performance degradation while trimming
- Include propulsive forces and moments

PHANTOM WORKS — BOEING

A prototype of a loosely coupled system for trimmed nonlinear aeroelastic of hypersonic air-vehicles has been demonstrated. It is modular and its execution can be distributed across the network for speed.

For this to become a production tool, several improvements are necessary. First, CFD analysis time has to be reduced significantly through improvements in algorithms and processor speed. While trimming, the structured grid topology that is used in this prototype is not suitable for all situations; when the control surface un-ports for example. When multiple control surfaces are involved, robustness of the process can also become an issue. The structured grid perturbation process also have difficulty producing viable CFD grids when aeroelastic deformation become large. The topology-free unstructured grid technology can easily address these problems.

Next, when the vehicle has multiple control surfaces, an optimizer is necessary to find the best trim setting. The optimized will help maintain aero performance or minimize degradation in performance while trimming. However, this will also increase the cost of the overall analysis.

Finally for hypersonic air-breathing vehicles, where propulsion contributes significantly to forces and moments and heat loads, including a propulsion module is necessary to obtain high-fidelity answers.